



The implications of the United Nations Paris Agreement on climate change for globally significant biodiversity areas

R. Warren¹ · J. Price¹ · J. VanDerWal² · S. Cornelius³ ·
H. Sohl³

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Abstract Climate change is already affecting species and their distributions. Distributional range changes have occurred and are projected to intensify for many widespread plants and animals, creating associated risks to many ecosystems. Here, we estimate the climate change-related risks to the species in globally significant biodiversity conservation areas over a range of climate scenarios, assessing their value as climate refugia. In particular, we quantify the aggregated benefit of countries' emission reduction pledges (Intended Nationally Determined Contributions and Nationally Determined Contributions under the Paris Agreement), and also of further constraining global warming to 2 °C above pre-industrial levels, against an unmitigated scenario of 4.5 °C warming. We also quantify the contribution that can be made by using smart spatial conservation planning to facilitate some levels of autonomous (i.e. natural) adaptation to climate change by dispersal. We find that without mitigation, on average 33% of each conservation area can act as climate refugium (or 18% if species are unable to disperse), whereas if warming is constrained to 2 °C, the average area of climate refuges doubles to 67% of each conservation area (or, without dispersal, more than doubles to 56% of each area). If the country pledges are fulfilled, an intermediate estimate of 47–52% (or 31–38%, without dispersal) is obtained. We conclude that the Nationally Determined Contributions alone have important but limited benefits for biodiversity conservation, with larger benefits accruing if

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✉ R. Warren
r.warren@uea.ac.uk

¹ Tyndall Centre and School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK

² Centre for Tropical Biodiversity and Climate Change and e-Research Centre, James Cook University, Townsville, Australia

³ WWF-UK, The Living Planet Centre, Rufford House, Brewery Rd, Woking GU21 4LL, UK

warming is constrained to 2 °C. Greater benefits would result if warming was constrained to well below 2 °C as set out in the Paris Agreement.

1 Introduction

Climate change poses risks to biodiversity, globally and regionally (Oppenheimer et al. 2014; O'Neill et al. 2017). Changes in phenology (Root et al. 2003; Parmesan 2007), species' ranges (Fischlin et al. 2007, Chen et al. 2011), ecological interactions (Post 2013) and primary productivity (Settele et al. 2014) have already been observed, and many studies have attributed such changes (as a whole or in part) to anthropogenic climate change (see Cramer et al. 2014 for a synthesis). A trait-based assessment of 16,857 species (Foden et al. 2013) estimated that 24–50% birds, 22–44% of amphibians and 15–32% of corals were highly vulnerable to climate change for a warming of approximately 2 °C above pre-industrial levels. Some species ranges are beginning to shift to track climate change, with more mobile species (e.g. butterflies) sometimes tracking it better (DeVitor et al. 2012), and less mobile ones tending to lag behind, in particular some plant species (Zhu et al. 2012). Species face a challenge in being able to track their preferred climate space across what is often an increasingly fragmented landscape (Settele et al. 2014), both in terms of the speed of movement required and any natural or anthropogenic obstacles to movement. Several studies have projected extensive range loss across large fractions of species globally or regionally due to climate change. For example amongst 50,000 species studied, $57 \pm 5\%$ of plants and $34 \pm 7\%$ of animals are projected to lose over half their climatic range for a warming of approximately 3.6 °C above pre-industrial levels (Warren et al. 2013), and there is evidence of increased extinction risks for warming of approximately 3 °C above pre-industrial levels (Foden et al. 2013; Urban 2015).

The Global 200 is a set of 238 irreplaceable or distinctive ecoregions identified by the global conservation organisation, the World Wide Fund for Nature (WWF) (Olson and Dinerstein 2002). These ecoregions comprise of areas which have some of the following characteristics: global rarity, high species richness, high species endemism and/or unusual ecological or evolutionary phenomena. They have provided a focus for many conservation activities. Over time, these areas have been consolidated by WWF into 35 'Priority Places' around the globe, which have been scientifically identified as being home to irreplaceable and threatened biodiversity, and/or present an opportunity to conserve the largest and most intact representation of their ecosystem (Fig. S0), and it is the terrestrial component of this subset (33 places) that is analysed here. Beaumont et al. (2011) analysed risks to ecoregions in terms of the number that are projected to be exposed to average monthly climates that differ from the baseline climate by more than two standard deviations in the year 2070. Whilst this is also a component of this study, we build upon this by examining a range of projected global temperature levels and by explicitly modelling the effects on species ranges and how these effects can be summarised in order to locate the climatic refugia where species can persist in the future.

Alongside the Paris Agreement of the UN Framework Convention on Climate Change (UNFCCC), countries put forward proposed post-2020 climate action in their Intended Nationally Determined Contributions (INDCs), which include pledges to limit or reduce greenhouse gas emissions by 2025 or 2030. As countries ratify the Paris Agreement, they drop the 'intended' and their pledge is converted into a Nationally Determined Contribution (NDC). The synthesis report by the UNFCCC secretariat 'Aggregate effect of the intended

nationally determined contributions: an update' (<http://unfccc.int/resource/docs/2016/cop22/eng/02.pdf>) shows that these contributions fall short of the emissions calculated to lie along a least-cost pathway towards limiting warming to even 2 °C above pre-industrial levels. However, the eventual level of warming will be strongly influenced by the level of emissions after 2030, with further reductions needed to limit warming to the Paris Agreement's 'well below 2 °C' or 1.5 °C. If no further emission reductions occur after achieving the first NDCs in 2030, an optimistic interpretation of the aggregate impact of the pledges corresponds to a 50% chance of limiting warming to 2.7 °C by the end of the century Climate Action Tracker's 'Effect of current pledges and policies on global temperature' (<http://climateactiontracker.org/global.html>). A recent assessment provided a range of 2.6–3.1 °C for NDC outcomes (Rogelj et al. 2016), whilst another estimates 3.2 °C (climateactiontracker.org). These are consistent with the scenarios explored here. If the Paris Agreement is not implemented successfully, and emissions continue to rise unchecked, then a business-as-usual warming of 4 °C or more may result by the end of the century (Collins et al. 2013).

Here, a climatic niche-based approach is used to assess whether and where biodiversity in terrestrial Priority Places around the world can persist under four future climate change scenarios, and in particular to explore the implications of countries' Paris Agreement pledges and to compare this with the implications if warming is constrained to 2 °C above pre-industrial levels, or if a no-mitigation business-as-usual warming of 4.5 °C occurs. The analysis also considers the ability of species to track climate changes by dispersal, and the potential role conservation management in facilitating this.

2 Methodology

This study makes use of the models developed by the Wallace Initiative (Warren et al. 2013). The Wallace Initiative has been subsequently updated and models the current and projected distributions of ~80,000 species from five terrestrial taxa (plants, amphibians, reptiles, birds and mammals) under various global climate change scenarios, with a spatial resolution of 20 km × 20 km, using a range of 21 climate models (general circulation models, GCMs, see [Supplementary Material](#)) in order to account for uncertainty in future climate projection, and emission and dispersal scenarios. The Wallace Initiative uses a climatic niche-based approach that has the advantage of being systematically applicable across the globe.

To examine the potential impacts of the Paris Agreement on the Priority Places, four climate change scenarios were considered:

1. Scenario BAU (business as usual): Without climate change mitigation, and in the absence of achieving the goals of the Paris Agreement, global annual average surface temperatures are projected to reach 4.5 °C above pre-industrial levels by the end of the century and act as a 'worst case' scenario in this study, although larger amounts of climate change are possible by 2100 (Collins et al. 2013).
2. Scenario INDC-high: Countries achieve 2030 INDC targets, but make no further emission reductions (pessimistic implication, 3.2 °C above pre-industrial levels by the end of the century).
3. Scenario INDC-low: Countries achieve 2030 INDC targets, but make no further emission reductions (optimistic implication, 2.7 °C above pre-industrial levels by the end of the century).

4. Scenario 2 °C: With stringent mitigation of anthropogenic greenhouse gas emissions, warming is limited to 2 °C above pre-industrial levels by 2100, and warming does not increase thereafter.

Projected climates are produced matching four different levels of warming at the end of the century (i.e. in the 2080s, by averaging the 30-year period 2071–2100) using the Representative Concentration Pathways (RCP) as follows (see [Supplementary Material](#)): RCP 8.5 is a proxy for the 4.5 °C no-mitigation BAU; RCP 4.5 is a proxy for the lower end of the INDC range (2.7 °C) and RCP 6.0 for the higher end (here 3.2 °C); and RCP 2.6 in the 2080s is a proxy for a 2 °C world.

The research encompassed three steps. Firstly, the extent to which the Priority Places are exposed to changes in climate, in terms of changes in seasonal temperature and precipitation, was explored in relation to the observed seasonal climate variability in each Priority Place. Secondly, the extent to which the species within Priority Place boundaries are exposed to unsuitable climates was explored for two cases: (i) in which species do not track their favoured climate and (ii) in which species attempt to track their favoured climate at a rate informed by dispersal rates reported in the literature (Warren et al. 2013). Case (i) is a proxy for conservation management without specific consideration of climate risk, whilst (ii) is a proxy for climate-smart conservation management in which protected areas are linked by corridors and species allowed to disperse freely. As evidenced from current range shifts and paleoecological literature, many species have moved in response to climate (see Warren et al. 2013 for review of dispersal); we refer to this as ‘adaptation’ (autonomous) in this paper. It should be noted that this excludes adaptation by other methods, such as the potential for some level of genetic or epigenetic changes or other types of behavioural change. Thirdly, for each of the five taxa in a Priority Place, the proportion of species at risk of extirpation (local extinction), and the spatial extent of climatic refugia, was calculated. A climatic refugium is defined in this study as an area where 75% of the total number of species presently found in a given taxon in a given Priority Place will still be found under a changed climate. The threshold chosen is a compromise between identifying the highest quality refugia and identifying the most land that might still be available for conservation given land use constraints.

For each of the four climate change scenarios, the objectives are to:

1. Quantify the exposure of each Priority Place, and the biodiversity within them, to changes in climate;
2. Quantify the proportion of species at risk of extirpation from Priority Places as a result of climate change alone;
3. Quantify the areal extent of climate change refugia in Priority Places;
4. Quantify the extent to which dispersal can reduce the projected impacts of climate change-induced range loss for the biodiversity of Priority Places; and
5. Quantify the extent to which climate change mitigation (i.e. reduction of anthropogenic greenhouse gas emissions) can reduce climate change-induced range loss for the biodiversity of Priority Places.

To address objective 1, we calculated the projected future exposure of Priority Places to changes in climate; projected climatic changes were averaged across the 21 GCM patterns and explored in the context of recent climate variability (see [Supplementary Material](#) for details of the observational climate datasets, projection of future climate change and exposure

calculation). In order to summarise the statistics across the Priority Places and seasons, a ‘Priority-Place-season’ metric was constructed, by totalling the number of seasons (up to 4) in which particular conditions were met (such as exceedance of a threshold) in each of the 33 terrestrial Priority Places. Thus, there were $33 \times 4 = 132$ Priority-Place-seasons in total. The results are presented as a percentage of Priority-Place-seasons meeting the conditions for each of the four climate change scenarios (ranging from 2 to 4.5 °C). The thresholds for inclusion in the summary statistics were derived from two 30-year observational periods, 1961–1990 and 1984–2013 (see [Supplementary Material](#)).

To address objectives 2–5, we calculated the exposure of biodiversity within each Priority Place to changes in climate using each of the 21 GCM regional climate change patterns in turn. To do so, we used terrestrial species distribution models developed with the Wallace Initiative, updated and improving upon the method described in Warren et al. (2013) (see [Supplementary Information](#) for further details). The results of this biodiversity analysis are shown in the complementary metrics of refugium persistence and extirpation risks. Broadly speaking, a Priority Place showing good refugium persistence for a given taxon will tend to have lower extirpation risks for that taxon and vice versa. The refugium metric allows identification of areas at lower risk whilst the extirpation risk metric was most suited to identifying areas at higher risk. To allow for the variation in regional climate change patterns, a refugium is identified in a grid cell only if at least 11 of the 21 GCM patterns agree in projecting its future existence. Extirpation risks are calculated separately for each of the 21 GCM patterns and then summarised to create an ensemble average of the risks in each grid cell. In order to summarise the statistics across Priority Places, a ‘Priority-Place-taxon’ metric was constructed, meaning one taxon in one Priority Place, i.e. for the 33 terrestrial Priority Places, there were $33 \times 5 = 165$ Priority-Place-taxa in total. From this, two complementary metrics were derived, the first by counting the number of taxa across Priority Places for which more than 75% of the Place can act as a refugium. A second metric was produced by calculating the average percentage of the area of a Priority Place that acts as a refugium, averaged across the five taxa and also across the Priority Places. The former metric indicates the total number of extensive refugia existing in Priority Places across the globe, whilst the latter indicates the average proportion of a Priority Place that still acts as a refugium under future climate change.

In addressing objective 4, we consider dispersal as a proxy to simulate a conservation strategy to climate change of joining existing ecosystems with connectivity gradients. Often, this may mean linking existing protected areas by protecting or restoring the habitat within the areas between them, thus allowing species to potentially disperse to areas becoming newly climatically suitable.

3 Results

The focus here is on a comparison of two scenarios—the no-mitigation BAU, in which future (average of the 30-year period 2071–2100) annual global average temperatures rise by 4.5 °C, and the scenario in which future warming is constrained to 2 °C above pre-industrial levels. See the [Supplementary Material](#) for a discussion of the findings for the intermediate ‘INDC’ scenarios.

3.1 Exposure of Priority Places to changes in climate

In the BAU scenario, future seasonal mean temperatures are projected to exceed the full range of historical seasonal temperatures across the Priority Places (Fig. [S1a](#), top right-hand green

triangle at 100%). In fact, under BAU, temperatures are projected to increase by an amount at least twice as great as the current natural variability in 91% of seasons across the terrestrial Priority Places (Fig. S1a, top right-hand red spot). That is, future seasonal average temperatures will greatly exceed anything experienced in the last half century.

Under the 2 °C scenario, the exceeded figure is reduced from 100 to 86% of seasons, and the greatly exceeded figure is substantially reduced from 91 to 12% of seasons (Fig. S1a, green triangles and red spots respectively). Overall, there is a progressive reduction of the amount of climate change to which the Priority Places are exposed as global warming is reduced.

Under the BAU scenario, wet day frequencies in terrestrial Priority Places were projected to rise or fall so that they are higher or lower than what has historically been experienced in ~ 20% of Priority-Place-seasons each (Fig. S1b, orange squares and blue diamonds). Under the 2 °C warming scenario, this reduced to ~ 1%. Thus, constraining warming to 2 °C above pre-industrial levels can largely constrain future average wet day frequency levels to lie within the previously experienced natural variability (Fig. S1b). The Priority Places projected to experience strong reductions in wet day frequency exceeding past variability in more than one season were Miombo Woodlands, Mediterranean, Madagascar, Cerrado-Pantanal, Southern Chile and West Africa.

The Miombo Woodlands Priority Place is the only one which has a season (June–August, JJA) in which reductions in seasonal precipitation are projected to fall below historically experienced levels. This is the case for all levels of warming examined. Miombo Woodlands was projected to be exposed to a greater reduction in precipitation, in the context of past natural variability, than any other Priority Place. In part, this is owing to the much greater variability in intra-annual precipitation than in intra-annual temperature. However, climate change is projected to increase drying in areas such as the Kalahari due to a shift in position of the Hadley cell where falling, drying air creates desert conditions (Lu et al. 2007) whilst observed desertification already exceeds that projected by climate models (Heffernan 2016).

Overall, the Priority Places most exposed to temperature changes exceeding past natural variability (at 2 °C global warming) were Miombo Woodlands, Coastal East Africa, Congo Basin, New Guinea, Sumatra and the Amazon-Guianas (Fig. S1c). Miombo Woodlands was slightly less exposed in terms of temperature change than the others listed here, but overall, it was most exposed to climate changes because of the concurrently projected large percentage reductions in precipitation referred to above.

3.2 Persistence of climatic refugia for biodiversity in Priority Places

Figure 1 shows the average areal extent of refugia across Priority-Place-taxa. By definition, without climate change, 100% of the area of all Priority Places acts as refugia. With no mitigation, under the 4.5 °C scenario, the average areal extent of refugia declines to 33% with autonomous adaptation by dispersal (see Section 2), (green spots), and to 18% in the absence of adaptation (red spots). With mitigation, under the 2 °C global warming scenario, the average areal extent of refugia is greater at ~ 67% with adaptation (green spots) and 56% in the absence of adaptation (red spots).

Constraining global average warming to 2 °C enables many species to continue (climatically) inhabiting areas presently occupied, because with lower amounts of warming, larger areas of Priority Places can act as climate refugia. For each level of warming, more refugia persist with adaptation (Fig. 1, compare red and green spots at a given temperature). The modelling indicates that mitigation has a greater total potential to preserve climatic refugia

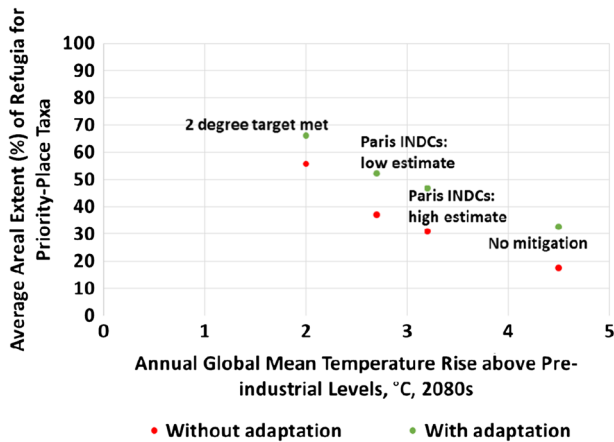


Fig. 1 Persistence of refugia in Priority Places with and without adaptation. The graph shows the average (across taxa and Priority Places) percentage of the area of a Priority Place that is projected to act as a refugium under the changed climate

for biodiversity in Priority Places than does adaptation (i.e. mitigating from 4.5 to 2 °C provides greater benefits than typical autonomous adaptation at 4.5 °C).

Under 4.5 °C warming and with adaptation, the proportion of Priority-Place-taxa for which refugia persist over at least 50% of the Priority Place area declines to 30% (Fig. S2a, blue diamonds). Furthermore, with no mitigation, only 14% Priority-Place-taxa have refugia occupying more than 75% of the Priority Place area (Fig. S2a, green triangles). The proportion of Priority Place area acting as refugia for taxa rises with mitigation: under the 2 °C scenario, the proportion of Priority-Place-taxa for which refugia persist over at least 50% of the Priority Place rises from 30 to 72% (Fig. S2a, blue diamonds). Likewise under the 2 °C scenario, the proportion of Priority-Place-taxa for which refugia persist over at least 75% of the Priority Place rises from 14 to 50% (Fig. S2a, green triangles).

Figure S2b shows the corresponding situation if species are not able to disperse. Comparison of the spots that have the same colour in Figs. S2a and S2b provides a measure of the benefit that adaptation provides to conservation of species. So the points at 4.5 °C in Fig. S2b show the situation without mitigation and without adaptation. In this case, the proportion of Priority-Place-taxa for which refugia persist over at least 50% of the Priority Place declines to 10% under BAU (Fig. S2b, blue diamonds), and only 2% of Priority-Place-taxa have refugia occupying more than 75% of the Priority Place area (Fig. S2b, green triangles). Under the 2 °C global warming scenario, the proportion of taxa for which refugia persist over at least 50% of the Priority Place reaches 58% (Fig. S2b, blue spots) and for 75% of the Priority Place reaches 29% (Fig. S2b, green triangles).

3.3 Projected species extirpation risks due to climatic change in Priority Places

In the absence of greenhouse gas emission reductions (4.5 °C warming), and if there are barriers to dispersal (i.e. without adaptation), almost 50% of the taxa presently found in Priority Places are at risk of extirpation (Fig. 2). Under the 2 °C scenario, the proportion exposed to extirpation is reduced to ~25% (Fig. 2). Considering now a different metric (the percentage of Priority-Place-taxa for which large proportions of species are at risk of

extirpation) it can be seen that under 4.5 °C warming, in over 90% of Priority Places, at least a quarter of taxa are projected to become vulnerable to extirpation due to climate change (Fig. S3, red spot); and in about 45% of Priority Places, at least half of the taxa become vulnerable to extirpation (Fig. S3, blue spot). Under the 2 °C scenario, the proportion of Priority Places in which at least a quarter of taxa are vulnerable to extirpation is reduced to 43% (Fig. S3, red spot), and the proportion in which at least half are vulnerable is reduced to 2% (Fig. S3, blue spot).

With adaptation, the proportion of taxa exposed to extirpation risks is reduced to 40% in the 4.5 °C scenario and 20% in the 2 °C scenario (Fig. 2, green spot). Thus, mitigation can make a significantly bigger contribution to avoiding extirpation risks than typical autonomous adaptation (Fig. 2, compare red and green spots and difference in highest and lowest red spots). In the 4.5 °C scenario, at least 25% of taxa in two thirds of Priority Places become vulnerable to local extirpation owing to climate change alone with adaptation but without mitigation (Fig. S3, red squares). Similarly, at least 50% of taxa in 30% of Priority Places become vulnerable to extirpation with no mitigation (Fig. S3, blue squares). Under the 2 °C scenario, if species can fully disperse, the proportion of Priority Places in which at least a quarter of taxa are vulnerable to extirpation is reduced to 29%, and the proportion in which at least half are vulnerable is reduced to 2% (Fig. S3).

3.4 Comparing projected risks across Priority Places

Figure 3a indicates the number of taxa for which refugia exist covering at least 75% of the area of a Priority Place, whilst Fig. 3b shows the average areal extent of refugia in each Priority Place, averaged across the five taxa. In both cases, adaptation is not included. In other words, Fig. 3a, b shows the Priority Places in which the refugia persist for the greatest amounts of climate change, i.e. ones where there are still some refugia even at 4.5 °C warming. These

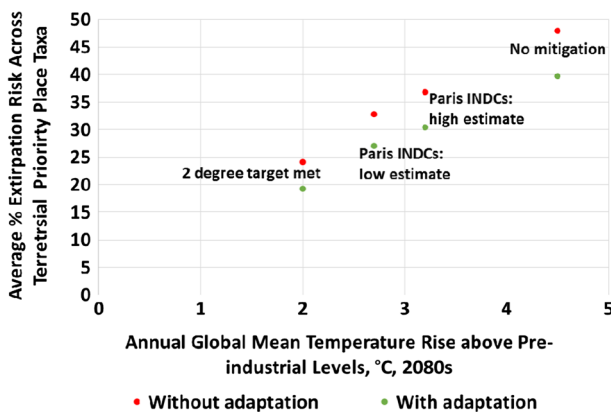


Fig. 2 Benefits of mitigation and adaptation (autonomous, i.e. dispersal) for biodiversity conservation in Priority Places. The graph shows the percentage of extirpation risks due to climate change alone averaged across Priority-Place-taxa. Mitigation has a critical influence on how many places become vulnerable to climate change even allowing for adaptation by dispersal (green spots). If species cannot adapt to changes in climate by dispersing (red spots), then even more species become vulnerable to climate change and mitigation is even more critical. Here, the red spot at 4.5 °C provides a worst case scenario in which there is no mitigation and no adaptation by dispersal. In each of the 33 Priority Places, there are (usually) 5 taxon analyses, and these are referred to as 'Priority-Place-Taxa'

places are located in Southern Chile, Eastern Himalayas and the Fynbos (Fig. 3b), with refugia persisting for some taxa even at 4.5 °C warming also in Sumatra and Borneo (Fig. 3a). The two indicators show that the Priority Places in which the most refugia are lost under 2 °C warming are Miombo Woodlands, Amazon-Guianas, Southwest Australia, African Rift Lakes, Cerrado and Coastal East Africa (Fig. 3a, b). In the case of no adaptation, the Priority Places in which extirpation risks were lowest as temperature rises globally by 4.5 °C are Southern Chile, Eastern Himalayas, Fynbos, Amur, Borneo and Sumatra (Fig. S4c shortest purple bars), whilst extirpation risks are the highest (without adaptation) as temperature rises to 2 °C in Miombo Woodlands, Southwest Australia, Amazon-Guianas, Coastal East Africa, Cerrado and African Rift Lakes (Fig. S4c, longest green bars). At 2 °C warming, nine Priority Places are projected to have refugia extending on average over 70% of their area (Fig. 4a): Southern Chile, Eastern Himalayas, Fynbos, Borneo, Sumatra, West Africa, New Guinea, Coral Triangle and Chihuahuan Desert.

3.5 Comparing projected benefits of mitigation across Priority Places

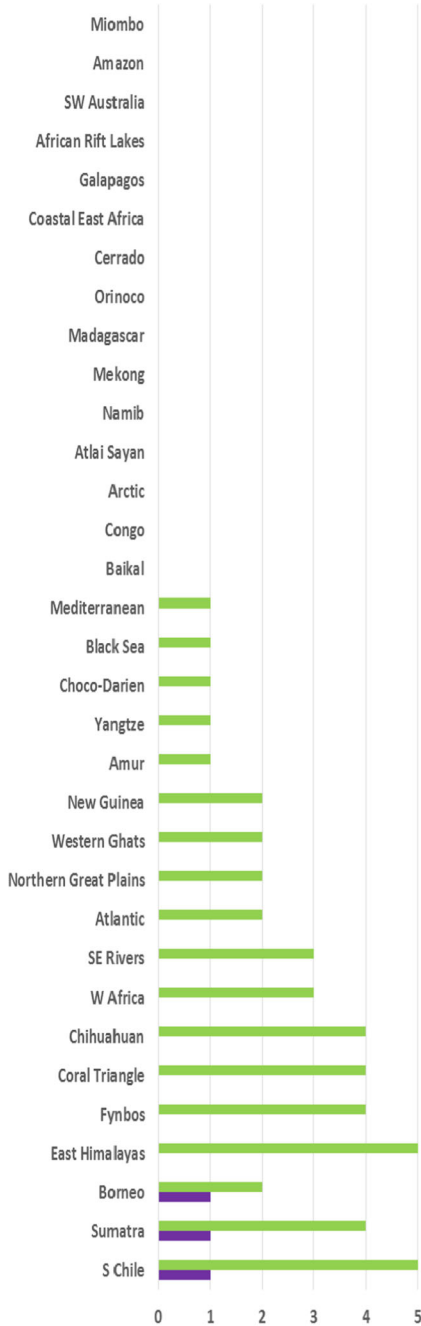
All Priority Places benefit from mitigation, with most taxa showing an improved persistence of refugia and/or a lower risk of extirpation with mitigation. Figure 3a, b shows the benefits of mitigating to 2 °C from the 4.5 °C BAU scenario in terms of avoiding refugium loss in Priority Places. The figures indicate large benefits of mitigation for refugia, in terms of both increasing the number of taxa for which large refugia exist (Fig. 3a) and also for greatly increasing the average extent of refugia across all taxa and Priority Places (Fig. 3b). The benefits of mitigation are seen by comparing the lengths of the purple and green bars in each of the figures.

Benefits of reducing global temperature rise from 4.5 to 2 °C in terms of avoiding loss of refugia across taxa in Priority Places are largest in the Eastern Himalayas (where over 75% of its area acts as a refugia for all five taxa at 2 °C yet for none at 4.5 °C), Fynbos, Coral Triangle, Chihuahuan Desert, Southern Chile, Sumatra, SE Rivers and West Africa (Fig. 3a, compare purple and green bars). These benefits are accompanied by increases in refugial area in all Priority Places, especially in Fynbos, Coral Triangle, Chihuahuan Desert, Borneo, New Guinea and Sumatra (Fig. 3b, compare purple and green bars). Some Priority Places such as Amazon-Guianas, Galapagos, Southwest Australia and African Rift Lakes, Orinoco and Namib-Karoo have little or no refugia at 4.5 °C but do so at 2 °C (Fig. 3b).

Benefits of reducing future global temperature rise to 2 °C (vs. 4.5 °C) in terms of avoided extirpation risks occur in all Priority Places, with most places showing that risks are reduced by ~40–60% (Fig. S4c). In absolute terms, the highest levels of avoidance are in Miombo Woodlands, Southwestern Australia and Namib-Karoo-Kaokoveld.

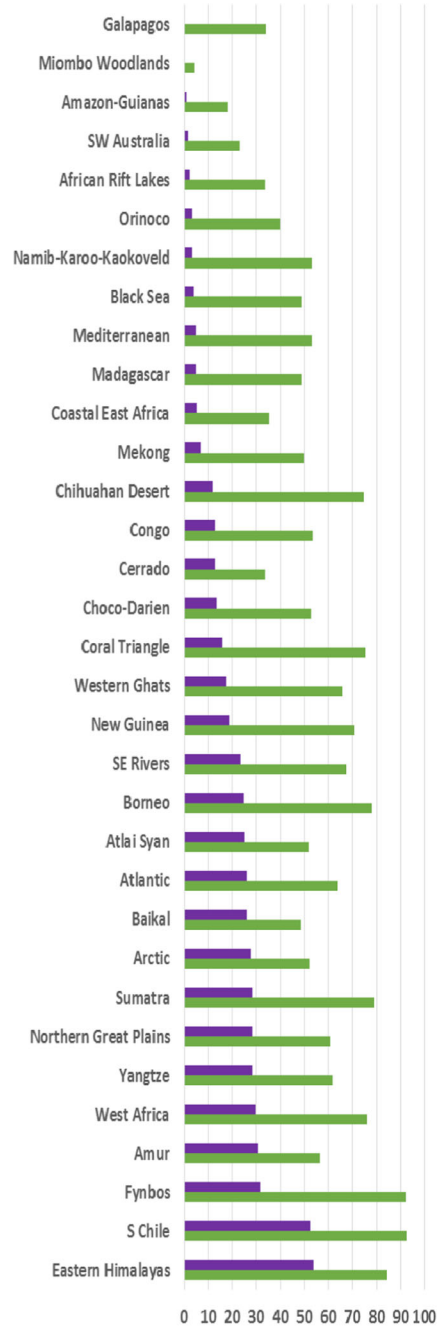
3.6 Comparing projected benefits of adaptation by dispersal across Priority Places

When adaptation is used to enable dispersal (corridors coupled with autonomous adaptation), the number and extent of refugia increase. Figure 4a, b shows how, for birds and mammals, the extent of refugia can in all areas be increased under a 2 °C global warming and under a 4.5 °C global warming should habitat be available. Under 2 °C warming, adaptation has a huge potential to preserve refugia for biodiversity in Amazon-Guianas, Cerrado, Coastal East Africa and Orinoco. Under 4.5 °C warming, large benefits from adaptation are seen in most Priority Places, especially in Amazon-Guianas. Similarly, with adaptation and 2 °C warming, the



Number of taxa (maximum 5) for which at least 75% of the area of a Priority Place protects >75% of species originally present, in each Priority Place

Place
 ■ 2°C >75% ■ 4.5°C >75%



Average across taxa of the % by area of each Priority Place that acts as a refugium, i.e. protects >75% of species originally present: without adaptation
 ■ 4.5°C ■ 2°C

Fig. 3 Benefits of mitigation if there is no adaptation; showing the Priority Places where the largest impacts on biodiversity are projected. Comparison at 2 and 4.5 °C global warming expressed in terms of (a) Priority Places for which 75% of their area can operate as a refugium for up to five taxa. The maximum number is 5 (i.e. plants, birds, mammals, reptiles, amphibians). Priority Places are arranged in order of *decreasing* climate change impacts. Impacts are greatest where no refugia remain (blank Priority Places at the top of the chart) and lowest where they remain even at 4.5 °C (purple bars at the bottom of the chart). Many more refugia remain at 2 °C than at 4.5 °C (middle and bottom of chart). The areas with the longest green bars are the ones which benefit the most from constraining warming to 2 °C: they have few or no refugia at 4.5 °C and three to five at 2 °C. (b) The average (across taxa) area of a Priority Place that can operate as a refugium. Many more areas acting as refugia remain at 2 °C than at 4.5 °C (middle and bottom of the chart). The areas with the greatest difference between purple and green bars are the ones which benefit more from constraining warming to 2 °C: they have few or no refugia at 4.5 °C and many at 2 °C

proportion of taxa for which more than 25% of the species originally present are still at risk of extirpation is reduced to the values shown in Fig. S5a (grey bars). The difference between the green and grey bars indicates the benefit of adaptation, which is particularly important in Madagascar, Amazon-Guianas, Orinoco River and Flooded Forests, Congo, Cerrado-Pantanal, Coastal East Africa and West Africa. (Fig. S5a). Average extirpation risks across taxa (Fig. S5c) also indicate general reductions in extirpation risks due to adaptation at 2 °C warming across all Priority Places, particularly Borneo, Sumatra and Choco-Darien. In this case for 11 Priority Places, all 5 taxa have less than 25% of species at risk of extirpation (Fig. S5a, lack of grey bars). In a further seven places, only one taxon has more than 25% of species at risk of extirpation (Fig. S5a). Even with 4.5 °C global warming, adaptation can somewhat reduce projected extirpation risks (Fig. S5b, compare purple and orange bars) by up to ~18%; however, the remaining impacts are high, so mitigation would be required to reduce them further.

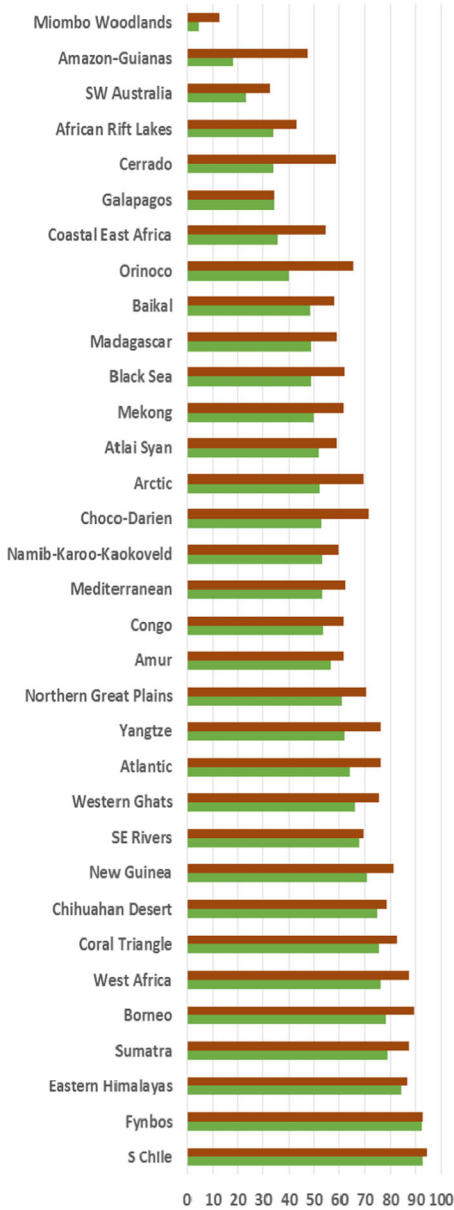
4 Discussion and conclusion

The benefits of climate change mitigation for biodiversity have been previously quantified globally in terms of global climatic range loss, using a similar basis to that described here. For example, Warren et al. (2013) find that constraining warming within this century to 2 °C above pre-industrial levels would avoid an estimated 60% of the climatic range loss compared to a 3.6–4 °C warming baseline scenario.

This study builds on the previous work by providing estimates of the benefits of mitigation and autonomous adaptation (through dispersal only), in terms of protecting biodiversity in one set of priority conservation areas for biodiversity—WWF’s terrestrial Priority Places. Similar results would likely be found in other subsets of the Global 200 ecoregions.

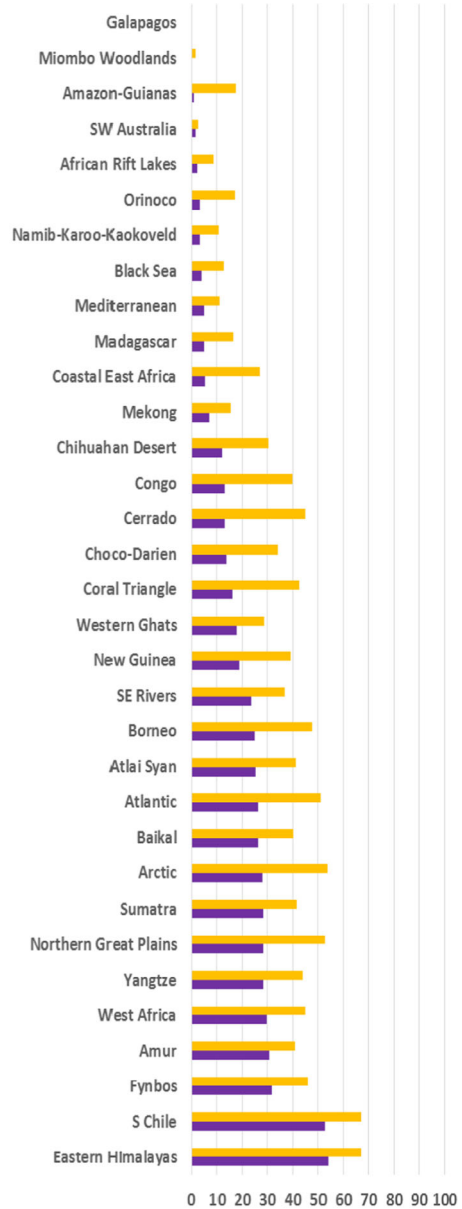
Large benefits are found to accrue from constraining warming to 2 °C above pre-industrial levels as compared with a BAU scenario in which global temperatures rise by 4.5 °C in terms of reducing risks to biodiversity in Priority Places. Significant but smaller benefits accrue from constraining warming to 2 °C above pre-industrial levels as compared with a ‘current pledge’ scenario in which global temperatures rise by 3.2 °C. However, adaptation is also important, irrespective of the level of warming.

There appears to be an almost linear relationship between warming in terms of annual global mean temperature rise above pre-industrial levels and species extirpation risks (Fig. 2, red spots). This indicates substantial benefits of reducing warming from 4.5 °C, where almost 50% of the species studied are at risk of extirpation, to NDC levels (2.7–3.2 °C) where ~33%



Average across taxa of the % by area of each Priority Place that acts as a refugium, i.e. protects >75% of species originally present

■ 2°C with adaptation ■ 2°C no adaptation



Average across taxa of the % by area of each Priority Place that acts as a refugium, i.e. protects >75% of species originally present

■ 4.5°C with adaptation ■ 4.5°C no adaptation

Fig. 4 Benefits of adaptation showing the Priority Places where the largest impacts on biodiversity are projected. Comparison at 2 °C (a) or 4.5 °C (b) expressed in terms of the average (across taxa) area of a Priority Place that can operate as a refugium. Priority Places are arranged in order of *decreasing* climate change impacts. Impacts are greatest where few or no refugia remain (Priority Places at the top of the chart) and lowest where they remain at 2 °C (green bars at the bottom of the chart, a) or even at 4.5 °C (purple bars at the bottom of the chart, b). More refugia remain if adaptation by dispersal occurs. The areas with the largest difference between brown and green bars (a) or orange and purple bars (b) are the ones which benefit the most from adaptation by dispersal. By the 2080s, this benefit is largely confined to birds and mammals since dispersal rates for other taxa are slow

remain at risk, and further to 2 °C, where ~25% remain at risk of regional extirpation. Similarly, there are substantial benefits to reducing warming seen in the areal extent of climate refugia in Priority Places which increased (allowing for adaptation) from ~33% with 4.5 °C warming to ~50% under the NDCs and to ~67% under 2 °C warming (Fig. 1, green spots).

The study also quantified key benefits arising from mitigating beyond current pledges (INDC-high, 3.2 °C warming) to 2 °C (see [Supplementary Material](#)) in all Priority Places, with benefits being particularly large in Amazon Guianas, Southwest Australia and Miombo Woodlands. Even without adaptation by dispersal, this mitigation doubles of triple refugial area in many Priority Places (see [Supplementary Material](#), Fig. S4a). With adaptation by dispersal, this level of mitigation increases refugial area by 10–30% in most Priority Places and doubles it in some (see [Supplementary Material](#), Fig. S4b). Benefits of reducing global temperature rise from 3.2 to 2 °C in terms of avoiding species extirpation from Priority Places (Fig. S4d, orange and green bars) also occur in all Priority Places, with risks being reduced by ~33%. Benefits of this mitigation remain similar in percentage terms when adaptation by dispersal is included (Fig. S4e).

Mitigation was found to have a greater total potential to reduce impacts than adaptation (Figs. 3 and 4). However, adaptation, in the form of removing barriers to species movement, is still critically important for conserving biodiversity—even more so if the global temperature rise is larger (compare red and green spots in Figs. 1 and 2; also Fig. 4a, b). At 2 °C, a smaller proportion of species are projected to be on the move, and hence the potential for these types of adaptation to assist conservation strategies is reduced. However, in some areas, adaptation is already critical for conservation even at 2 °C, for example, in Amazon-Guianas, Cerrado, Coastal East Africa and Orinoco. At 4.5 °C warming, larger benefits of adaptation are seen in most Priority Places, but especially Amazon-Guianas, where almost no refugia exist otherwise. This finding of the critical importance of conservation management in protecting biodiversity from climate change in these areas is significant.

Our findings result from an extensive global analysis of projected changes in the climatic ranges of plants and animals based on the outputs of 21 GCMs. However, it should be borne in mind that the estimates of climatic range shifts could be over- or under-estimated, due to the uncertainties in regional climate projection and the need to summarise this by using levels of model agreement, and also the effects of factors that could not be included in the simulations. These include interactions between species, the effects of extreme weather events (McDermott-Long et al. 2016), the ability or otherwise of species to utilise novel climates (Williams and Jackson 2007) and regime shifts. It should be noted that changes in fire regimes are implicitly included since fire frequency has a strong relationship with bioclimatic variables (Krawchuk et al. 2009). However, overall, these results should be considered conservative as any modelling exercise projecting biodiversity impacts which does not include the influence of extreme weather events potentially greatly under-estimates the likely risk for species. Indeed, the influence of extreme weather events has been shown to cause local extirpation of butterfly

species (Oliver et al. 2015) or mass die-offs of mammals and birds (Welbergen et al. 2008) and, depending on their frequency and intensity, might be more important than changes in mean climate in driving local extirpation (Bauerfeind and Fisher 2014). This research is designed to inform decision-makers by providing information about the implications of the Paris Agreement for conservation globally and also about how conservation management in the form of provision of corridors can contribute to the protection of species from the effects of climate change. Detailed spatial analyses of each individual Priority Place would also be important to assist conservation planners working at the local scale. The expectation is that further mitigation to limit global temperature rise to well below 2 or 1.5 °C as outlined in the Paris Agreement would further reduce risk of extirpation and increased area of refugia.

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References

- Bateman BL, Murphy HT, Reside AE, Mokany K, VanDerWal J (2013) Appropriateness of full-, partial- and no-dispersal scenarios in climate change impact modelling. *Divers Distrib* 19:1224–1234
- Bauerfeind SS, Fisher K (2014) Simulating climate change: temperature extremes but not means diminish performance in a widespread butterfly. *Popul Ecol* 56:239–250
- Beaumont LJ, Pitman A, Perkins S, Zimmermann NE, Yoccoz NG, Thuiller W (2011) Impacts of climate change on the world's most exceptional ecoregions. *PNAS* 108:2306–2311
- Bernie D, Lowe J (2014) Future temperature responses based on IPCC and other existing emissions scenarios. AVOID2 WPA.1 Report 1. Available at www.avoid.uk.net
- Chen IC, Hill JK, Ohlemüller R, Roy DB, Thomas CD (2011) Rapid range shifts of species associated with high levels of climate warming. *Science* 333:1024–1026
- Collins M, Knutti R, Arblaster J et al (2013) Long-term climate change: projections, commitments and irreversibility. In: Stocker TF, Qin D, Plattner G-K et al (eds) *Climate change 2013: the physical science basis*. Cambridge University Press, Cambridge, pp 1029–1136
- Cramer W, Yohe GW, Auffhammer M et al (2014) Detection and attribution of observed impacts. In: Field CB, Barros VR, Dokken DJ et al (eds) *Climate change 2014: impacts, adaptation, and vulnerability*. Cambridge University Press, Cambridge, pp 979–1037
- DeVictor V, van Swaay C, Brereton T, Brotons L, Chamberlain D, Heliola J, Herrando S, Julliard R, Kuussaari M, Lindström A, Reif J, Roy DB, Schweiger O, Settele J, Stefanescu C, Van Strien A, Van Turnhout C, Vermouzek Z, Wallis M, DeVries I, Wynhoff I, Jiguet F (2012) Differences in the climatic debts of birds and butterflies at a continental scale. *Nat Clim Chang* 2:121–124
- Fischlin A, Midgley GF, Price JT et al (2007) In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) *IPCC climate change 2007: impacts, adaptation and vulnerability*. Cambridge Univ. Press, Cambridge, pp 211–272
- Foden WB, Butchart SH, Stuart SN, Vié J-C, Akçakaya HR, Angulo A et al (2013) Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. *PLoS One* 8(6):e65427
- Heffernan O (2016) The mystery of the expanding tropics. *Nature* 530:20–22
- Krawchuk MA, Moritz MA, Parisien MA, Van Dorn J, Hayhoe K (2009) Global pyrogeography: the current and future distribution of wildfire. *PLoS One* 4:e5102

- Lu J, Vecchi GA, Reichler T (2007) Expansion of the Hadley cell under global warming. *Geophys Res Lett* 34: L06805
- McDermott-Long O, Warren R, Price J, Brereton TM, Botham MS, Franco AMA (2016) Sensitivity of UK butterflies to local climatic extremes: which life stages are most at risk? *J Anim Ecol* 86:108–116
- Moss RH et al (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463: 747–756. <https://doi.org/10.1038/nature08823>
- O'Neill B, Oppenheimer M, Warren R et al (2017) Key risks of climate change: the IPCC reasons for concern. *Nat Clim Chang* 7(1):28–37
- Oliver TJ, Marshall HH, Morecroft MD, Brereton T, Prudhomme C, Huntingford C (2015) Interacting effects of climate change and habitat fragmentation on drought-sensitive butterflies. *Nat Clim Chang* 5:1–6
- Olson DM, Dinerstein E (2002) The global 200: priority ecoregions for global conservation. *Ann Mo Bot Gard* 89:199–224
- Oppenheimer M, Campos M, Warren R et al (2014) Emergent risks and key vulnerabilities. In: Field CB, Barros VR, Dokken DJ et al (eds) *Climate change 2014: impacts, adaptation, and vulnerability*. Cambridge University Press, Cambridge, pp 1039–1099
- Osborn TJ et al (2016) Pattern-scaling using ClimGen: monthly-resolution future climate scenarios including changes in the variability of precipitation. *Clim Chang* 134:353–369
- Parmesan C (2007) Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Glob Chang Biol* 13:1860–1872
- Phillips SJ, Dudik M (2008) Modelling of species distributions with MaxEnt: new extensions and a comprehensive evaluation. *Ecography* 31:161–175
- Post E (2013) *Ecology of climate change: the importance of biotic interactions*. Princeton University Press, USA ISBN: 9780691148472
- Rogelj J, den Elzen M, Höhne N, Fransen T, Fekete H, Schaeffer R, Sha F, Riahi K, Meinhausen M (2016) Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nat Clim Chang* 534:631–639
- Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. *Nature* 42:57–60
- Settele J, Scholes R, Betts R et al (2014) In: Field CB, Barros VR, Dokken DJ et al (eds) *Climate change 2014: impacts, adaptation, and vulnerability*. Cambridge University Press, Cambridge, pp 271–359
- University of East Anglia (UEA) Climatic Research Unit, Harris IC, Jones PD (2014) CRU TS3.22: Climatic Research Unit (CRU) Time-Series (TS) version 3.22 of high resolution gridded data of month-by-month variation in climate (Jan. 1901–Dec. 2013). NCAS British Atmospheric Data Centre, 24 September 2014. <https://doi.org/10.5285/18BE23F8-D252-482D-8AF9-5D6A2D40990C>
- Urban M (2015) Accelerating extinction risk from climate change. *Science* 348(6234):571–573
- Warren R, VanDerWal J, Price J, Welbergen JA, Atkinson I, Ramirez-Villegas J, Osborn TJ, Jarvis A, Shoo LP, Williams SE, Lowe J (2013) Quantifying the benefit of early mitigation in avoiding biodiversity loss. *Nat Clim Chang* 3:678–682
- Welbergen J, Klose SM, Markus N, Eby P (2008) Climate change and the effects of temperature extremes on Australian flying foxes. *Proc Roy Soc B* 275:419–425
- Williams JW, Jackson ST (2007) Novel climates, no-analog communities, and ecological surprises. *Front Ecol Environ* 5(9):475–482
- Yesson C, Brewer PW, Sutton T, Caithness N, Pahwa JS et al (2007) How global is the global biodiversity information facility? *PLoS One* 2(11):e1124
- Zhu K, Woodall CW, Clark JS (2012) Failure to migrate: lack of tree range expansion in response to global climate change. *Glob Chang Biol* 18:1042–1052